LASE measurements of water vapor, aerosol, and cloud distributions in hurricane environments and their role in hurricane development

S. Ismail[1,*], E. V. Browell[1], R. A. Ferrare[1], S. A. Kooi[2], L. Brasseur[2], A. Notari[2], L. Petway[1], V. Brackett[2], M. Clayton[2], M.J. Mahoney[3], J. Halverson[4], S. Rizvi[5], T. N. Krishnamurti[5], R. Kamineni[5]

[1]NASA Langley Research Center, Hampton, VA, [2]SAIC Corp. Hampton, VA, [3]California Institute of Technology/Jet Propulsion Laboratory, [4]Univ. of Maryland Baltimore County, [5]Florida State Univ.

*Tel: 1-757-864-2719; Fax: 1-757-864-7790; E-mail: s.ismail@larc.nasa.gov

ABSTRACT

The LASE system was used during the NASA CAMEX-4 field experiment to characterize the moisture field associated with hurricanes over the Atlantic Ocean during August-September 2001. LASE measured high resolution moisture, aerosol, and cloud distributions not available from conventional observations. LASE water vapor measurements were compared with dropsondes to evaluate their accuracy. Water vapor in the mid- and upper-troposphere varied by more than an order of magnitude indicating dynamical and thermodynmical processes associated with hurricanes. LASE water vapor measurements were used to assess the capability of hurricane models to improve their track accuracy by 100 km on 3 day forecasts using Florida State University models.

1. Introduction

The main objective of the NASA Convection and Moisture Experiment (CAMEX-4) was the study of tropical cyclone (hurricane) development, tracking, intensification, and landfalling impacts using NASA-funded aircraft and surface remote sensing instrumentation. CAMEX-4 was conducted from Jacksonville Naval Air Station, FL during August-September 2001. In hurricane forecast models, moisture and diabatic processes are not properly modeled due to the scarcity of high resolution tropical tropospheric humidity fields. High resolution moisture data are needed to initiate hurricane prediction models that include fundamental physical processes (Krishnamurty, 1991). In order to obtain a more comprehensive understanding of the moisture environment associated with the hurricanes, the Lidar Atmospheric Sensing Experiment (LASE) was configured to fly on the NASA DC-8 aircraft during CAMEX-4. In this paper a description of LASE instrument is followed by LASE measurements and comparisons with dropsonde observations. An example of the impact of LASE measurements on hurricane tracks is presented using available CAMEX-3 data obtained over Hurricane Bonnie during 1998. A discussion of preliminary results using LASE CAMEX-4 data is presented.

2. LASE Instrument and Operations

The LASE system was developed at the NASA Langley Research Center as an autonomous DIAL system to measure atmospheric water vapor, aerosols, and clouds from the high altitude ER-2 aircraft (Browell et al., 1997). The laser system consists of a double-pulsed Ti:sapphire laser that operates in the 815-nm absorption band of water vapor and is pumped by a frequency doubled Nd:YAG laser. During CAMEX-4, LASE operated locked to a strong water vapor absorption line at 817.223 nm and electronically tuned to other spectral positions on the absorption line (side-line positions). In this mode, LASE transmitted up to three (on- and off-line) wavelength pairs that together permitted profiling of water vapor over the entire troposphere. Total output laser energy at 815-nm was about 100 mJ at each of the on- and off-line laser pulses transmitted at 5 Hz. This energy was nominally split in a 7:3 ratio for transmission in nadir and zenith orientations, respectively. The nadir detector system used two silicon avalanche photo diodes and three digitizers to cover a large signal dynamic range (10^6).

3. LASE Measurements

The DC-8 conducted 13 flights during CAMEX-4 including 5 long duration flights over Hurricanes Erin and Humberto, and Tropical Storms (TS) Chantel and Gabrielle. LASE operated in the nadir and zenith mode simultaneously during these flights. Flights over Hurricane Erin and TS Gabrielle were considered to be Optimal Data Assimilation Flights (ODAF) and some of the main objectives of these flights were: assess the impact of high resolution water vapor and wind measurements on forecasts of hurricane intensity and track; obtain high resolution water vapor measurements to characterize water vapor inflow regions; evaluate ER-2 and DC-8 dropsonde water vapor measurement performance in conjunction with NOAA HRD synoptic surveillance flights. The LASE capability for profiling tropospheric water vapor, aerosols, and clouds has been demonstrated during previous field experiments (Browell et al., 1997, Ismail et al., 2000). LASE measurements from CAMEX-4 were used to derive aerosol scattering ratios, water vapor mixing ratios and relative humidity profiles. Range corrected and background subtracted off-line signals were used in deriving the scattering ratios using atmospheric number densities from DC-8 dropsondes (Ismail et al., 2000). Molecular, water vapor, aerosol, and cirrus cloud extinctions were used in removing biases due to signal attenuation. The scattering ratios were normalized to measurements match with a clean region value observed at a high altitude occurring at least in one location over the entire flight. The resolutions of aerosol scattering data are 60 m (vertical) and 600 m (horizontal). Water vapor measurements were retrieved from LASE data by taking into consideration all atmospheric and instrument effects as outlined by Browell et al. 1997. LASE signals were vertically smoothed and horizontally averaged to obtain nominal water vapor profile resolutions of 330 m (vertical) by 20 km (horizontal) and 1 km (vertical) by 40 km (horizontal) for the data obtained in the nadir and zenith directions, respectively. Relative humidity profiles were derived using the water vapor profiles from LASE and temperature profiles derived from the DC-8 Microwave Temperature Profiler (MTP). The MTP is a radiometer that passively measures the thermal emission from oxygen molecules at 3 frequencies between 55 and 59 GHz -- each at 10 elevation angles; these 30 measurements of brightness temperatures are then used to retrieve a temperature profile. For a nominal flight altitude of 10 km, the rms error in the MTP retrieved temperature profile is <1 K within 2 km of the aircraft, and degrades to <2 K within the range of 1 km above the surface. Relative humidity profiles are computed using LASE water vapor profiles and MTP temperature profiles as described by Ferrare et al. (2000).

LASE measurements were made on September 10, 2001 to characterize the moisture environment associated with Hurricane Erin that was situated at 35.5 N latitude and 65.1 W longitude. Sustained winds of 105 kts and a clear eye with a diameter of 30 km were associated with this storm. This mission included 8 dropsondes from the ER-2 operating in the stratosphere into the eye of the storm, 9 dropsondes from DC-8 in all quadrants of the hurricane. This mission was conducted in close coordination with measurements from NOAA operational aircraft. The DC-8 flew at an altitude of 28000 ft and circumnavigated the hurricane. The DC-8 flight tract overlaid on satellite imagery is shown in Figure 1. LASE nadir measurements of water vapor mixing ratio, aerosol scattering ratio, and relative humidity profiles are also shown in the figure. Blank regions indicate lack of reliable measurements due to cloud influence/attenuation. Moisture levels were high in the northeastern quadrant with water vapor mixing ratios exceeding 5 g/kg up to and above 6 km where a number of rain bands were located. Dry air was located in the subsiding region in the northwest of the storm and more than an order of magnitude variations in water vapor in the mid- and upper-troposphere were observed. Regions of high relative humidity (>80%) were well correlated with observation of clouds with aerosol scattering ratios exceeding 6.

LASE measured the fine structure of moisture field associated with Tropical Storm Gabrielle on September 15, 2001. After landfall over Florida, the storm reemerged over the Atlantic and was located near 30 N latitude and 79 W longitude. The storm exhibited unusual structure with convection in the north and northeastern quarters and dry air in the south and southeast. The presence of dry air entrainment in the southeast prevented rapid redevelopment of the storm. A time series of water mixing ratios that vary nearly by two orders of magnitude (from about 0.03 g/kg to >2.0 g/kg) from an altitude of 8 km is shown in Figure 2. The flight tract went from SE to north of the storm and from north to south and SE in the two segments of the time series. From the LASE measurements, profiles of water vapor mixing ratio, RH, and scattering ratio profiles been derived. These measurements were used to define the moisture structure of the storm, for comparisons with dropsondes from DC-8, and to provide input to hurricane forecast models developed at the Florida State University (FSU).

4. Comparisons with Dropsondes

Dropsondes from the Airborne Atmospheric Profiling System were released from the DC-8 periodically during flights and provide wind, temperature, and moisture data that are used in hurricane forecast models. LASE measurements of water vapor field were made continuously and comparison of moisture profiles from the two sensors was one of the objectives of these measurements. An example of the comparison of water vapor from the two sensors taken during the Hurricane Erin flight is shown in Figure 3. The error bars on the LASE profile represent the 1-σ standard deviation due to the combination of the variation of water vapor and the precision of measurements over the averaging interval of 2 minutes centered at 19:04 UT (Figure 1). The two measurements agree in general and profile the general features in lower and mid-tropospheric water vapor. The measurements agree very well up to about 1.2 km altitude and the dropsonde are slightly dryer (by about 10%) in the mid- to upper-troposphere. This is perhaps due to a generally known dry bias in the Vaisala humidity sensor due to outgassing by desiccants and aging of the sensors (Wang et al., 2002). Kooi et al. in a companion paper have presented more analysis and comparisons of LASE and dropsonde measurements during CAMEX-3 and CAMEX-4 show a dry bias of 15% and 5% respectively.

5. LASE Measurements and Hurricane Forecast Models

Dropsonde and LASE data obtained during CAMEX-3 were used in the FSU models to analyze the impact on hurricane forecast by using a spectral statistical interpolation technique with $0.94^{\circ}X0.94^{\circ}$ resolution in horizontal and 14 vertical levels in the vertical (Rizvi et al., 2001). The first guess for the analysis was derived from the ECMWF global reanalysis at 0.5° resolution. The LASE data alone did not much affect the wind analysis, however it had a significant impact on the moisture analysis. The LASE analysis gave an indication of a slightly drier region away from the hurricane while it showed a spiraling of both dry and wet bands close to its center. When LASE data were used along with the dropsonde observations, the hurricane intensity and their structure were well represented and the forecast tracks produced from the reanalyzed initial condition improved. An example of the improvement in the 120 hour track forecast for Hurricane Bonnie on August 24, 1998 is shown in Figure 4. Inclusion of both LASE and dropsonde data further improved track forecast. In general the inclusion of LASE moisture data had a reduction of error by 100 km on 3 day forecasts, in the sense that the forecast tracks were closer to the corresponding best observed hurricane tracks. These tests were performed on Hurricanes Bonnie, Danielle and Georges of 1998. In addition to the LASE moisture profiles, data sets from as many as 100 dropsondes per day from at least 5 research aircrafts were included. Separate tests were made from without and with the LASE moisture data sets where all other data sets were included in all numerical experiments. The availability of the LASE profiles of moisture helps in the definition of moisture convergence which is a key parameter in the parameterization of cumulus convection that provides the heating for these hurricanes. For the CAMEX-4 analysis, at present, only LASE and dropsonde data from the CAMEX-4 and the ECMWF data are available and other data sets including the NOAA P-3 are needed to conduct a full analysis. Preliminary results indicate that the inclusion of LASE and dropsonde data improve track forecast for Hurricane Erin and Humberto. Details of the analysis will be presented in this paper.

6. Conclusions

From LASE measurements during CAMEX-4 high resolution moisture, aerosol scattering ratio, and RH profiles were derived to obtain a more complete understanding of the structure and thermodynamic environment associated with Hurricanes Erin and Tropical Storm Gabrielle. LASE measurements showed large variations of moisture in the upper-troposphere that represent dynamics associated with these weather systems. LASE comparisons with dropsondes show a general agreement between the two sensors and a slight dry bias in the sondes in the upper troposphere. . The availability of the LASE profiles of moisture helps in the definition of moisture convergence which is a key parameter in the parameterization of cumulus convection that provides the heating for these hurricanes. Analysis of the impact of moisture is in progress. Inclusion of LASE data during CAMEX-3 showed that, in general, these data reduced track error by 100 km on 3 day forecasts.

5. Acknowledgements

We thank Dr. Ramesh Kakar, NASA Program Manager for Atmospheric Dynamics and Remote Sensing for providing financial support for the deployment of LASE during CAMEX-4. Work at the Jet Propulsion Laboratory, California Institute of Technology, was carried out under contract with the National Aeronautics and Space Administration.

References

E. V. Browell, S. Ismail, W. M. Hall et al., in *Advan. in Atmos. Remote Sensing With Lidar*, A. Ansman, R. Neuber, P. Rairoux, and U. Wandinger (Eds.), Springer, pp 289-295, 1997.

R. Ferrare, E. V. Browell, S. Ismail et al., Selected papers 20^{th} ILRC, A. Dabas et al., (eds), 317-320, 2001.

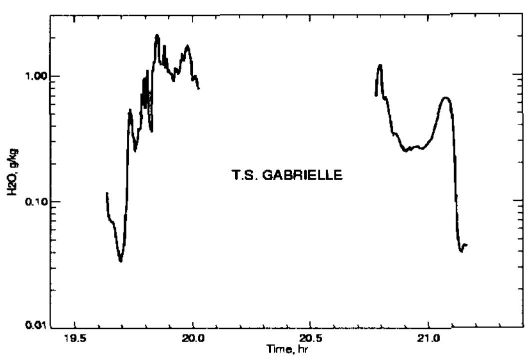
S. Ismail, E.V. Browell, R. Ferrare et al., JGR 105, 9903-9916, 2000.

T. N. Krishnamurti, J. Xue, H. S. Bedi et al., Tellus, 43AB, 53-81, 1991.

S. R. H. Rizvi, E. Bensman, T. V. Kumar, A. Chakraborty, FSU Report #01-08, April 2001.

J. Wang, H. L., Cole, D. J. Carlson et al., (in press), Jtech, January 2002.

Figure Captions:
Figure 3. A time series of LASE measurements at an altitude of 8 km over a flight across and back over T. S. Gabrielle from a dry air region in the SE quadrant.
Figure 2. Comparison of LASE and dropsonde profiles in the vicinity of Erin.
Figure 4. FSU model track forecast



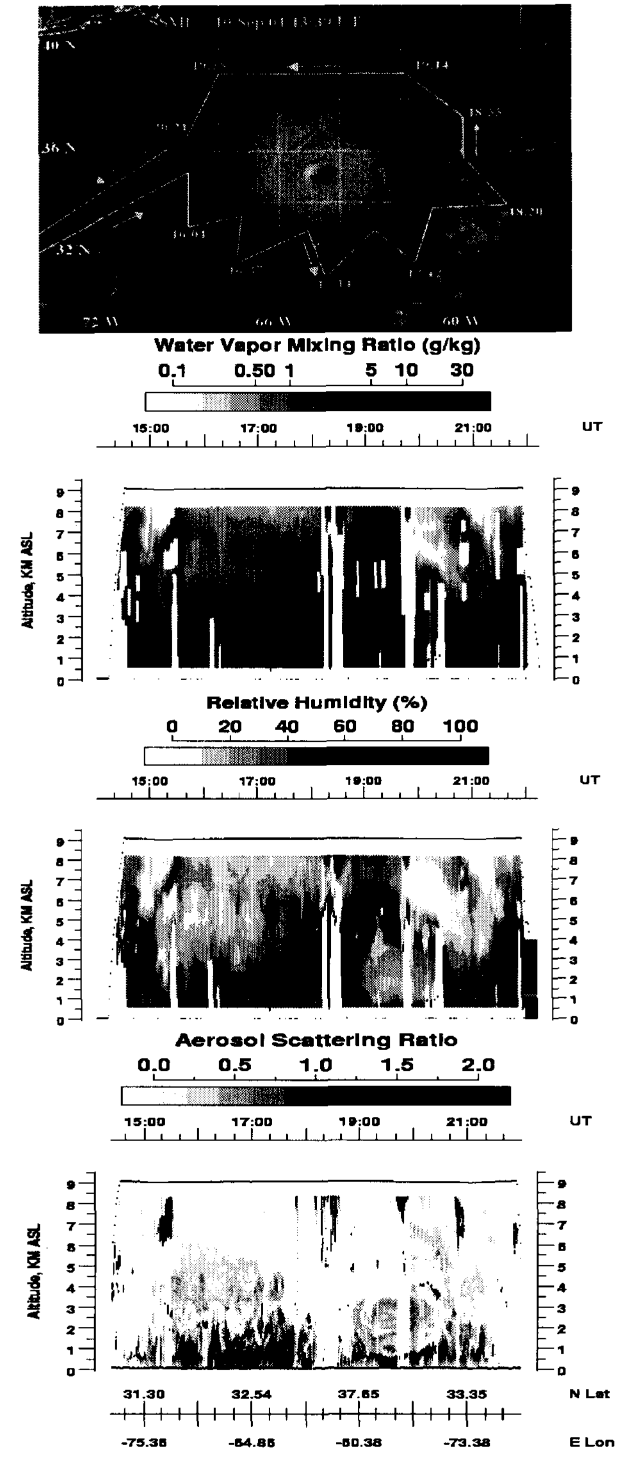
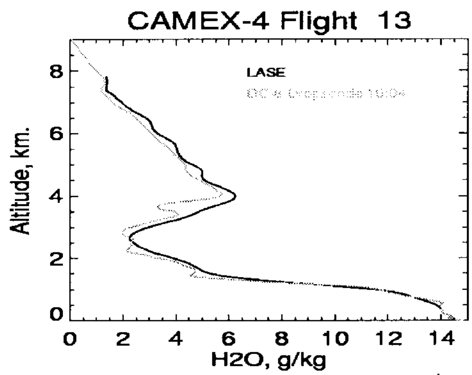
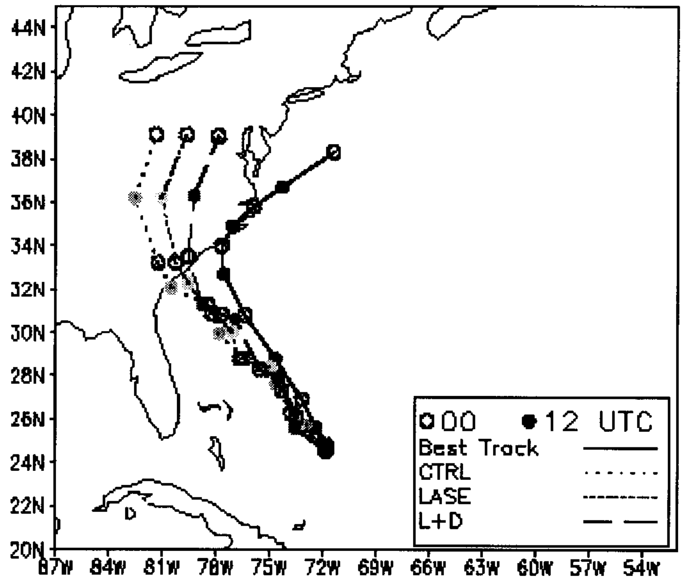


Figure 1. (top) CAMEX-4 DC-8 flight track around Hurricane Erin on September 10, 2001. (bottom) water vapor mixing ratio, relative humidity, and aerosol scattering ratio derived from LASE nadir


CAMEX-4 Flight 13
LASE
Altitude, km.
H2O, g/kg
0
2
4
6
8
0
2
4
6
8
10
12
14

(a) 120 Hour forecast track of Hurricane Bonnie
IC: 00 UTC 24 August 1998



(b) 84 Hour forecast track of Hurricane Bonnie
IC: 12 UTC 26 August 1998